

# THE ESSENTIAL REQUIREMENTS FOR COMPATIBLE CARS IN FRONTAL COLLISIONS

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## ABSTRACT

The work reported here forms part of a research project that is being undertaken to further the understanding of compatibility in car to car collisions and develop crash evaluation procedures that are suitable for consumer and legislative testing. For frontal impact, full scale crash testing, accident analysis case studies and supportive finite element modelling studies have been used to identify the major factors that influence compatibility. One result is that the geometrical interaction of car structures has a large effect and it is now believed that obtaining good structural interaction is an essential prerequisite for frontal impact compatibility. Having achieved this, the next step is to control the global stiffness of the cars to ensure that they are able to absorb the collision energy, with minimal occupant compartment intrusion, without compromising the vehicle's deceleration pulse profile. Frontal impact evaluation procedures are being developed, which use load cell wall measurements to assess a car's compatibility. The current state of development of possible procedures is described, with an emphasis on results from full width deformable barrier tests. Procedures to assess side impact compatibility may be added following further research. This reported research is being used to support the European Enhanced Vehicle-safety Committee (EEVC) and the International Harmonisation of Research Activities (IHRA) Compatibility Working Group activities, and is funded by the Department of the Environment, Transport and the Regions (DETR).

## INTRODUCTION

Following the introduction of the European Frontal and Side Impact Directives in October 1998, compatibility offers the next greatest potential benefit for improving car occupant safety and reducing road casualties. For the UK, this can be illustrated by examining the STATS19 accident database. Approximately 60 percent of all car occupant casualties occur in accidents where the car collides with another vehicle, the type of accident that compatibility primarily addresses (Table 1). A

Renault study has suggested that improved compatibility could reduce the number of fatalities and serious injuries by as much as a third in accidents where a car collides with one other vehicle (1). If this was realised in GB it would have equated to a saving of 278 fatalities and 3511 serious injuries in 1999 in accidents where the car collided with one other vehicle. In addition, benefits should also occur in multi-vehicle and many single vehicle accidents.

**Table 1.**  
**Distribution of car occupant casualties by collision type in GB**

| Collision Type                     | Fatalities   |              | Serious Injuries |                |
|------------------------------------|--------------|--------------|------------------|----------------|
|                                    | 1998         | 1999         | 1998             | 1999           |
| Single car                         | 491<br>(29%) | 495<br>(30%) | 5132<br>(26%)    | 4825<br>(26%)  |
| Car to one other vehicle           | 821<br>(49%) | 835<br>(50%) | 11179<br>(57%)   | 10533<br>(57%) |
| Car to more than one other vehicle | 364<br>(22%) | 348<br>(20%) | 3467<br>(18%)    | 3144<br>(17%)  |

In 1995, on behalf of the DETR, TRL commenced a project to research compatibility. This ongoing work is being used to support the European Enhanced Vehicle-safety Committee (EEVC) and the International Harmonisation of Research Activities (IHRA) compatibility working groups. This project aims to identify how vehicle safety may be improved by developments to their structures and subsequently implement these changes in the vehicle fleet. This requires an understanding of the factors that influence compatibility and the development of new or modified evaluation procedures to bring about greater compatibility. The project also aims to identify the potential benefits that could be obtained from improved compatibility. In a complex area, the approach taken for this work was to focus on car to

car frontal impact and car to car side impact separately, in order to understand the influencing factors more clearly. This paper reports on the frontal impact studies only.

## FRONTAL IMPACT COMPATIBILITY

Continuing the drive of the European Frontal Impact Directive and EuroNCAP, the work performed to date has focused on the structural performance of the vehicles, with the aim of providing a safe environment in which the restraint system can operate. This approach is supported by the results from a recent European accident analysis study which shows that for the UK over 70 percent of the AIS 3+<sup>1</sup> injuries received by belted occupants were contact induced as opposed to restraint system induced (2). Once the structure provides a safe environment within which the restraint system can operate, the next step for further improvement will be to control the compartment deceleration pulse. Following this, intelligent restraint systems could offer a way to cope with higher compartment decelerations, and give the occupant an optimised ride-down for a variety of impact severities. Previously reported work conducted for this project has investigated the effect of the shape of the deceleration pulse on the performance of current restraint systems (3).

The results from this project have overturned the original views about compatibility, which thought that mass and mass ratio were the dominant factors. Now it is clear that although mass has an effect on stiffness, which affects intrusion, the most important factor is structural interaction. Good structural interaction is required to ensure that cars interact predictably to absorb the impact energy, in the designed manner with minimal occupant compartment intrusion. Without this essential prerequisite, the energy absorbing capability of the frontal structure is, generally, dramatically reduced. This leads to excessive compartment intrusion. Once good structural interaction has been achieved, some form of stiffness matching between vehicles is necessary to ensure that the impact energy is absorbed without exceeding the strength of the occupant compartment. The evidence leading to these conclusions is presented below, together with proposals for test procedures to assess and control compatibility.

## Structural Interaction

Real road accident configurations are very varied; impact angle, overlap, impact point and speed are just a few of the parameters describing an accident. The concentration of structural stiffness in elements such as the frontal lower rails can adversely affect safety performance in accidents. Misalignment of these stiff lower rails is normal and can result in high passenger intrusion levels due to inadequate energy absorption by these stiff elements. This can manifest itself in a number of different ways, such as override, where one vehicle tends to ride up over the other, or the penetrating fork effect where the stiff members of one vehicle penetrate the soft areas of the other vehicle due to lateral misalignment.

The override effect has been seen in accidents even with recent car designs that perform well in the EuroNCAP assessment. An example of this effect is described. The accident occurred between a Volvo S40 and a VW Polo (mass ratio 1.26). The collision was head on with approximately 30 percent overlap. The young healthy female driver of the Polo was killed but the driver of the S40 survived with serious injuries. There was poor structural interaction between the frontal structures of the two vehicles resulting in the Volvo overriding the Polo. Comparing the relative deformation of the upper and lower rails for the two cars shows this. The S40 upper rail showed little deformation whereas the Polo upper rail was significantly deformed (Figures 1 and 2). In contrast, the S40 lower rail was lifted up whereas the Polo lower rail was bent down and out. The result of this non-ideal structural performance was that the energy absorption efficiency of both cars was reduced, which lead to additional compartment intrusion.

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<sup>1</sup> An Abbreviated Injury Scale 3+ (AIS3+) injury severity level relates to a severe or greater injury.



**Figure 1. Volvo S40, note the small deformation of the upper rail and the lifting of the lower rail indicating that this car has overridden the VW Polo.**



**Figure 2. VW Polo, note the large deformation of the upper rail and the downward deformation of the lower rail indicating that this car has been overridden by the Volvo S40.**

In summary, the overriding was a major contributory factor to the large intrusion seen in the Polo at fascia rail level, in comparison to the small intrusion in the S40. Even so, the mass and stiffness difference between the cars was likely to have contributed as well.

The lack of good structural interaction between current vehicle designs is further illustrated by comparing the relative performances of the Peugeot 806 and VW Sharan in EuroNCAP tests with those in a car to car impact test. The EuroNCAP test results show that there was less door aperture deformation for the 806 compared to the Sharan (Figure 3).



**Figure 3. The Peugeot 806 (above) showed less door aperture deformation than the VW Sharan (below) in EuroNCAP tests<sup>2</sup>.**

However, in the car to car test the Sharan (Galaxy)<sup>3</sup> overrode the 806 with the result that the 806 occupant compartment experienced far greater intrusion than in the equivalent EuroNCAP test (Figure 4).

The sensitivity of structural interaction with current cars has been illustrated in previous work (3). This showed how a 100 mm difference in ride height for an impact between two identical cars resulted in a significantly different structural performance for each car. The raised car overrode the lowered car resulting in greater intrusion in the lowered car at fascia rail level. In contrast there was greater intrusion in the raised car in the footwell area.

<sup>2</sup> Photographs courtesy of EuroNCAP.

<sup>3</sup> Please note that the MPV in the car to car test was a Ford Galaxy. However, the VW Sharan and Ford Galaxy are structurally identical.



**Figure 4. Peugeot 806 (above) is overridden by VW Sharan (Galaxy) (below) in car to car impact resulting in increased occupant intrusion in 806<sup>4</sup>.**

These results show that in order to achieve a compatible fleet an essential prerequisite is good structural interaction. Until vehicle designs enable structures to interact better in car to car impacts, any compatibility improvements in stiffness matching are unlikely to be fully realised. To achieve good structural interaction, the implications for car design are that they will require better vertical, lateral and shear connections. These connections will increase the number of active load paths into the main energy absorbing structures. This will help to ensure that predictable behaviour occurs over a wider range of impacts, hence improving crashworthiness performance.

The introduction of such connections will most likely result in cars having a more uniform frontal stiffness distribution. Following this logic, a test procedure has been proposed. This test uses load cell wall measurements, from a full width frontal impact test with a deformable element, to assess and control a car's frontal stiffness distribution. It is recognised that

one failing of this proposed test concept is that it would not exercise the shear connectivity between load paths such as the upper and lower rails. However, it is unlikely that a car could achieve a homogeneous stiffness distribution without good shear connections.

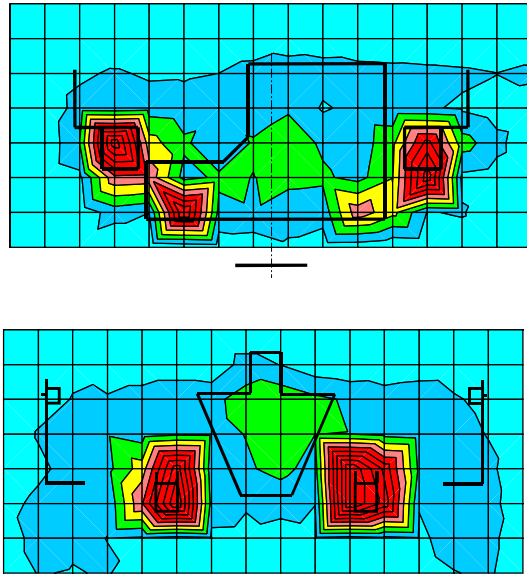
#### **Full Width Deformable Barrier Test**

A series of full width tests with a deformable element have been performed with current cars varying in size from small family to Sports Utility Vehicle (SUV) using an impact velocity of 56 km/h. High resolution load cell wall measurements were recorded using a wall which consisted of 128 load cells of size 125 mm by 125 mm arranged in an 16 by 8 matrix. The deformable element used, consisted of a 150 mm deep aluminium honeycomb face with a longitudinal crush strength 0.34 MPa.

The depth and stiffness of the barrier were chosen primarily for two reasons. The first was so that, compared to a rigid wall test, the initial high decelerations at the front of the car were attenuated to make the test more representative of a vehicle to vehicle impact. The second was to ensure that the element had little effect on the occupant compartment deceleration pulse so that the test could also be used as a frontal impact test similar to US FMVSS 208. Previous work has found that this deformable face also reduces the magnitude of the engine loading on the wall, which may be more realistic as in accidents the engine can rotate or move horizontally or vertically. However, the results of the latest series of tests have shown that local hard points on the car can dramatically reduce loading from adjacent structures indicating that the barrier depth and / or stiffness may be need to be altered. FE modelling studies are currently addressing this issue.

To demonstrate the potential of this test procedure, the load cell wall results for a family car exhibiting features likely to benefit compatibility such as an engine subframe load path have been compared to those for a less compatible vehicle, a SUV. A subjective visual inspection of contour plots of the peak force measured on each load cell shows a greater spread of the higher loads for the family car caused by the presence of the engine subframe indicating the potential of this test procedure (Figure 5). Please note that the load cell array was raised 125 mm for the SUV.

<sup>4</sup> Photographs courtesy of ADAC.



**Figure 5. Comparison of load cell peak forces for family car (above) and SUV (below). Note, vehicle main structure is superimposed on plots to show load paths.**

In order to assess the stiffness homogeneity in a more objective manner, further analyses of the results tried various statistical techniques to differentiate the stiffness homogeneity of these vehicles. These included the application of coefficient of variance (CV), skewness and kurtosis techniques to the load cell wall data for ten cars. The coefficient of variance (CV), which is defined below, was found to be the most promising parameter to date.

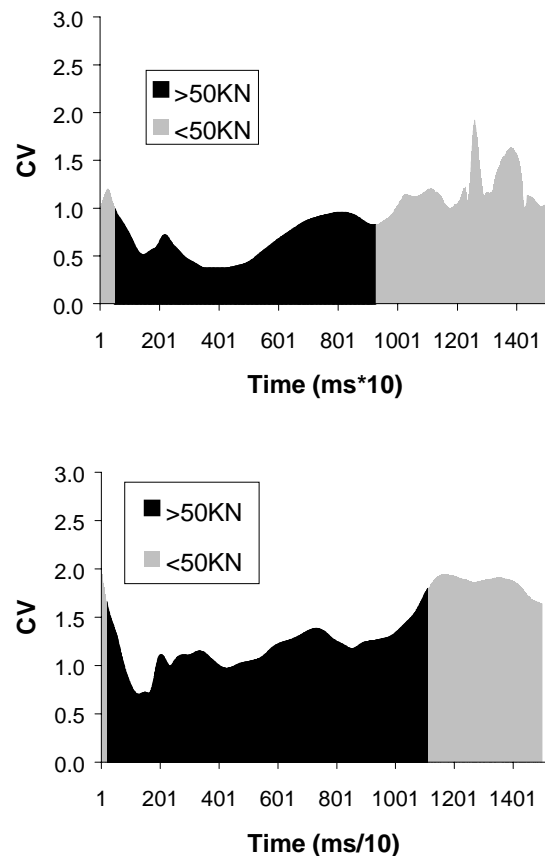
$$CV = \text{Standard Deviation} / \text{Mean}$$

Inclusion of all load cell wall data in an analysis would have distorted any potential homogeneity measure by including many unloaded cells. To solve this problem, a rectangular block of load cells was chosen to represent the vehicle footprint, using the criterion that at least one load cell in the outside row or column must experience a peak load greater than 5 kN.

Two problems were found in applying the CV technique to the load cell wall data set. Firstly, the CV was too variable when the mean value of the load was low at the beginning and end of the impact, because small changes in the loading caused large changes in the standard deviation. Secondly, the bridging of load cells by structural members of the vehicle sometimes caused changes in the CV, although these were smaller than expected. Bridging

is the term used to describe the loading of two or more load cells by one structural member of a vehicle, such as the longitudinal. The low load variability problem was solved by defining that the CV measure was only applied at times when the total load on the wall was greater than 50 kN. The bridging problem was solved by averaging the outputs from four adjacent load cells and allocating this value to one of the cells in a stepwise manner for each of the load cells. Calculating the CV, following the above process, proved to be stable as the implementation of an artificial 5 percent noise on the load cell force input only created a 1 percent difference to the output values.

Using the above methodology, the CV was calculated for the family car and SUV and shows substantially higher values for the SUV (Figure 6). The dark shaded area defines the time for which the CV is considered valid, i.e. when the total wall loads are over 50 kN.



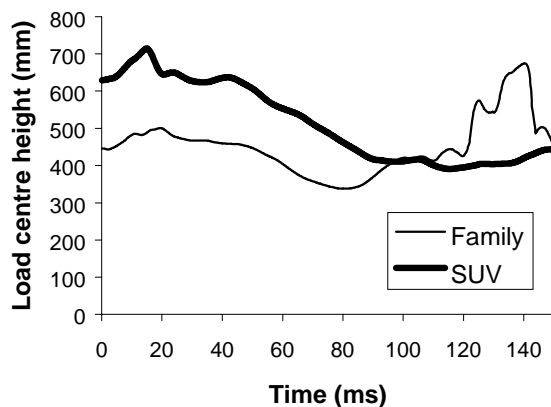
**Figure 6. Coefficient of variance (CV) for family car (above) and SUV (below) showing higher values for the SUV.**



To enable easy direct comparison of the results the CV was integrated over the defined impact time and normalised to a time of 100 ms to give a single value. For the more compatible family car this was 0.756 whereas for the less compatible SUV it was 1.174. The difference in these values demonstrates the potential of this parameter as a tool to evaluate the stiffness homogeneity of car frontal structures.

The above proposal could be used to control a vehicle's stiffness homogeneity over its frontal crash footprint, but to ensure good structural interaction these footprints need to overlap. One way to achieve this would be to control the height of the centre of force measured on the load cell wall as proposed by NHTSA (4). The centre of force height may also need to be controlled throughout the duration of the impact. In addition, a limit controlling a vehicle's minimum footprint area will be required.

The centre of force height measured from the ground for the family car and SUV show a substantial difference as might be expected (Figure 7). The average height weighted by the load on each cell was 438 mm and 587 mm, respectively. To ensure good structural interaction between these vehicles this difference needs to be reduced. However, for the cars tested, not including SUVs, the force centre height range was 31 mm indicating a large overlap of the car's footprints, which shows the potential for good structural interaction.



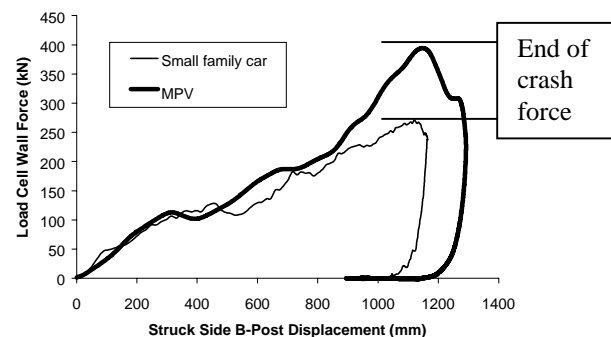
**Figure 7. Variation of centre of force height showing substantial difference between family car and SUV.**

### Structural Stiffness

The primary aim of compatibility is to achieve minimal occupant compartment intrusion levels in both vehicles, in car to car collisions. If we consider a car, of mass  $m$ , impacting a rigid barrier with an

initial velocity of  $v$  and assume that its occupant compartment undergoes minimal intrusion, then that car's front structure has an energy absorption capability of at least its initial kinetic energy,  $\frac{1}{2}mv^2$ . Simple mathematics shows that if two cars of differing masses crash together with a closing velocity of less than  $2v$ , then there is sufficient energy absorption capability available to absorb the impact energy with no more occupant compartment intrusion than in the rigid barrier test (5). In order to ensure that the energy absorption capability is available for use, then the stiffness of the two cars needs to be matched. However, in general, heavier vehicles have a higher global stiffness than lighter vehicles, as heavier vehicles have to absorb their larger kinetic energy in approximately the same deformation length. In a car to car collision, this leads to greater intrusion in the less stiff car as it absorbs more energy relative to an equivalent barrier test (1,6). Previous work has shown that occupants of lower mass vehicles have higher injury risks due to both lower vehicle mass and stiffness (7). There is, however, no certainty that the stiffness differential between small and large cars will continue to exist at the current ratio.

The 'interface force' is defined as the force between the car and the barrier in a car to barrier test or the force between the car and the opposing car in a car to car test. It can be obtained using a load cell wall or by the measurement of the deceleration of the constituent parts of the vehicle (1,3). The interface force for a small family car and an MPV in a 64 km/h Offset Deformable Barrier (ODB) test is shown as a function of B-pillar displacement (Figure 8). The end of crash force is the interface force at the end of crash and is shown (Figure 8).

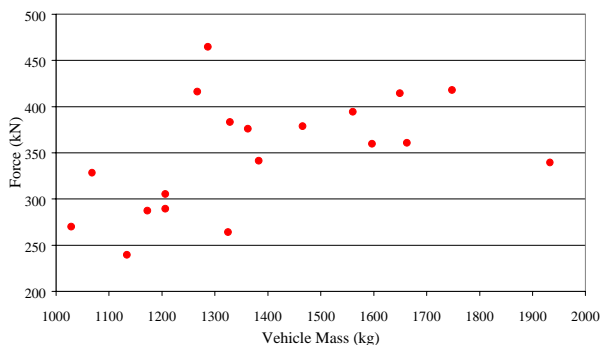


**Figure 8. Interface force plotted as function of B-pillar displacement for small family car and MPV showing end of crash force.**

To control a vehicle's frontal stiffness and occupant compartment strength, two test procedures are proposed. To control the frontal stiffness, the end of

crash force would be measured using a load cell wall in a 64 km/h ODB test and limited to a maximum value, yet to be determined. To ensure that the occupant compartment strength is sufficient to withstand the loads imposed by an opposing vehicle, a second ODB test is proposed at an increased impact speed in which the end of crash force would be measured and controlled to exceed a minimum value yet to be determined. To assess the feasibility of these proposals and determine suitable end of crash force values, much further work is required. The inertial contribution of the power train to the interface force should be taken into account in this work.

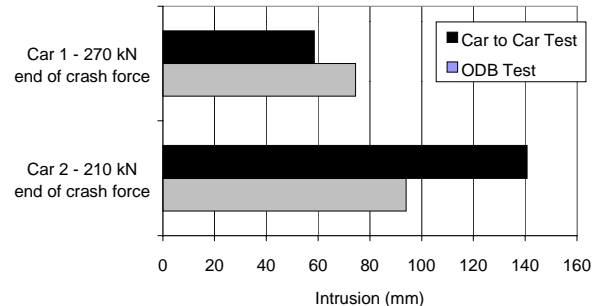
As part of this continuing investigation, load cell wall end of crash force measurements have been taken for a number of recent EuroNCAP tests (Figure 9). These results indicate that, in general, lighter cars have smaller end of crash forces. However, it was noticeable that each mass range of cars has a wide spread of 'end of crash' force levels, which would tend to indicate that some uniformity across the mass range should be possible to create a more compatible car fleet.



**Figure 9. End of crash force measurements for recent Euro NCAP tested cars.**

In order to test the validity of using the end of crash force concept to control a car's stiffness, two car to car crash tests were conducted with a 50 percent overlap and a closing speed of 112 km/h. The height of the main load carrying structures of these vehicles were checked to help ensure that good structural interaction would occur in the tests. The first test was between two small cars with a mass ratio of 1.01 with different end of crash force values, 270 kN and 210 kN. These values were measured in a 64 km/h ODB test. The result was that the car with the higher end of crash force, indicating a higher stiffness, absorbed less than its share of the impact energy. As a result, it suffered less intrusion relative to that measured in the ODB test, compared to the car with the lower end of

crash force (Figure 10). The intrusion values shown are an average of four measurements, footwell intrusion, fascia displacement and A-pillar waist and sill displacement. This result supports the validity of the end of crash force concept.



**Figure 10. Intrusions measured in ODB and car to car test showing car with higher end of crash force suffered less intrusion relative to its performance in an ODB test.**

In contrast, the second test was between a small car and a family car with a mass ratio of 1.3 with similar end of crash force values, 270 kN and 290 kN, respectively, indicating similar stiffnesses. For this test the expected result was that the intrusion measured in each vehicle would be similar relative to that measured in the ODB test. Unfortunately, the family car overrode the small car, which caused greater intrusion in the small car than expected. This shows that without good structural interaction any stiffness matching will not be effective.

As mentioned above, to ensure that the occupant compartment strength is sufficient to withstand the loads imposed by an opposing vehicle, a second ODB test is proposed at an increased impact speed in which the end of crash force would be measured and controlled to exceed a minimum level. The test would not require instrumented dummies.

A number of trials have been conducted to investigate the possibility of using an already crashed vehicle for this test to save the use of an expensive prototype. However, this 'double testing' approach proved to be infeasible so a 'new' car will have to be used for this test. Reusing a car from a full width barrier test was shown to be unrepresentative of a single impact test because of the different structural behaviour. For example, the engine to firewall interaction was much greater for the double impacted car compared to the single impacted one. To reuse a car from an ODB test was deemed infeasible because it would not always be possible to latch the driver's door following the first test.

To investigate what impact speed should be used for this test other researchers have performed ODB tests at 80 km/h, (50 percent greater KE than 64 km/h) (8). They concluded that if the passenger compartment became unstable, repeatability was poor. They also found that if the occupant compartment intrusion was large the driver's femurs could support the car's structure. To attempt to overcome these problems future tests will be conducted at lower impact speeds, possibly 72 km/h, (25 percent greater KE than 64 km/h) and require a stable occupant compartment.

### **SUMMARY OF PROPOSED TEST PROCEDURES FOR COMPATIBILITY AND FRONTAL IMPACT**

In order to address the issues above and improve frontal impact compatibility, it is proposed that the use of three tests for both compatibility and frontal impact should be considered.

1. A full width deformable barrier test at 56 km/h with a high resolution load cell array behind the deformable element. From the load cell measurements the centre of force height over time could be controlled. The force distribution could be controlled using a technique such as the Coefficient of Variance (CV). This should encourage the development of frontal structures that behave in a more homogeneous manner, which should lead to an improvement in structural interaction in car to car impact. Damage to the deformable face might also be used as a check for load concentrations that are not revealed by the load cell wall.
2. An Offset Deformable Barrier (ODB) test at 64 km/h with a load cell array behind the deformable element. From the load cells, the car's global stiffness characteristic could be assessed using the end of crash force concept. In the future, control of the pulse shape could be used to limit the occupant compartment deceleration pulse and restraint loading. Control of the centre of force height could also be included for this test as well as the full width test.
3. A second ODB test with a load cell wall at an elevated speed to assess the strength of the passenger compartment. This test would not require instrumented dummies.

For frontal impact, one of the advantages of these proposed tests is that they have quite different deceleration pulses and hence would not encourage

optimisation of the performance of restraint systems to one pulse. The full width would generate a 'hard' deceleration pulse on the vehicle and restraint system, whereas the 64 km/h ODB test would generate a 'soft' pulse.

At this stage, it is not expected that the introduction of evaluation procedures detailed above would have any detrimental effect on car to car side impacts or impacts with pedestrians, HGV's, or other obstacles, indeed they are expected to be beneficial.

### **CONCLUSIONS**

The results from this project indicate that in order to improve structural performance for better compatibility in frontal impact, cars need to interact in a predictable manner to absorb the impact energy with minimal occupant compartment intrusion over a broad range of collision types. To achieve this, an essential prerequisite is good structural interaction. Following this, some form of stiffness matching between vehicles will be necessary to ensure that the impact energy is absorbed without exceeding the strength of the occupant compartment.

In order to address these issues and improve compatibility, outlines for three possible test procedures to assess and control both compatibility and frontal impact have been proposed. This is an evolving area and further work is required to develop these outlines to a level suitable for consumer or legislative test procedures.

Implementation of these three test procedures should be sufficient to control intrusion and provide a safe environment within which the restraint system can operate. This should address contact induced injuries but not restraint induced injuries. A next step to reduce injuries caused by the restraint system could be to control the shape of the interface force profile or the car's deceleration pulse. This would provide a deceleration pulse, which would enable optimum performance of the restraint system.

### **ACKNOWLEDGEMENTS**

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